Capability Roadmap Workshop for In-Situ Resource Utilization (ISRU)

APIO Workshop
Nov. 30, 2004

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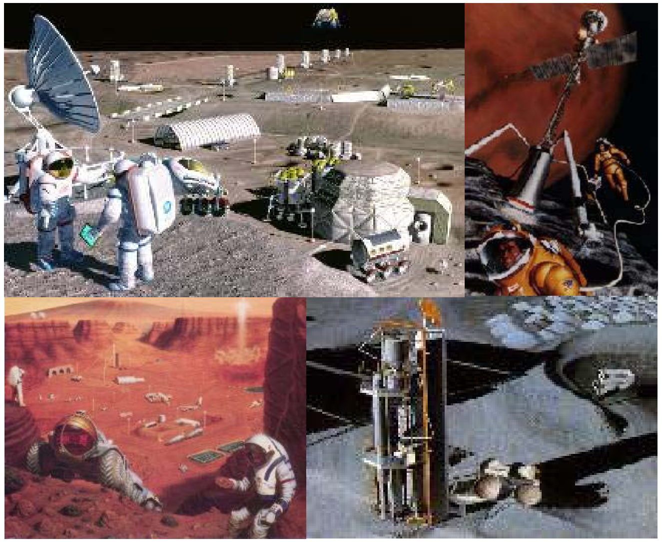


Why Develop ISRU For Human Exploration?

Cost, Risk, and Benefit of human/robotic exploration are dependant upon:

- Mass delivered from Earth
- Surface operation and exploration effectiveness (No. of EVAs, crew size, science, etc.)
- Minimizing hazards and critical failures

ISRU *Enables* lower mission mass & cost

- In-situ propellant production **reduces Earth launch mass** or number of launches required
- Life support consumable production can amount to **several tens of MT of savings**, depending on degree of recycling and functional redundancy; emergency cache
- In-situ production capabilities can reduce mission abort scenarios thereby reducing costs
- Use of lunar produced oxygen/propellant could further reduce mission mass

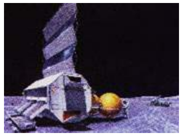
ISRU E*nable*s "Flexible" & "Sustainable" planetary surface exploration

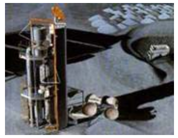
- In-situ production of oxygen ***enables*** **long-term surface EVA** (even with 100% closed loop life support)
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts and surface infrastructure (power, habitats, shielding, etc.) enables sustainability and self-sufficiency
- ISRU can provide dissimilar redundancy thereby reducing mission risk

Critical resources are available on Mars

- Atmospheric resources (nitrogen, argon, and carbon dioxide) are widely available
- Water may be widely available – however form and location require further investigation

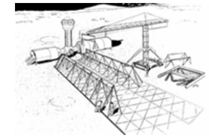
Uses of Space Resources for Robotic & Human Exploration





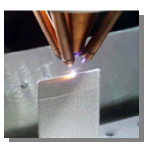

Mission Consumable Production

- ➢ **Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles**
- ▪ Fuel cell reagents for mobile (rovers, EVA) & stationary backup power
- ➢ **Life support consumables** (oxygen, water, buffer gases)
- ▪ Gases for science equipment and drilling
- ▪ Bio-support products (soil, fertilizers, etc.)
- ▪ Feedstock for in-situ manufacturing & surface construction

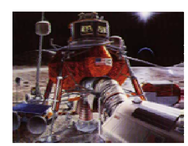
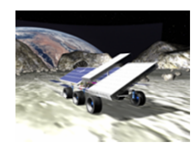

Surface Construction

- ➢ **Radiation shielding for habitat & nuclear reactors from in-situ resources or products** (Berms, bricks, & plates; water; hydrocarbons)
- ➢ **Landing pad clearance**, site preparation, roads, etc.
- ▪ Shielding from micro-meteoroid and landing/ascent plume debris
- ▪ Habitat and equipment protection




Manufacturing w/ Space Resources

- ➢ **Spare parts manufacturing**
- ▪ Locally integrated systems & components (especially for increasing resource processing capabilities)
- ▪ High-mass, simple items (chairs, tables, chaises, etc.)


Space Power & Utilities

- ▪ Storage & distribution of mission consumables
- ▪ Thermal energy storage & use
- ▪ Solar energy (PV, concentrators, rectennas)
- ▪ Chemical energy (fuel cells, combustion, catalytic reactors, etc.)

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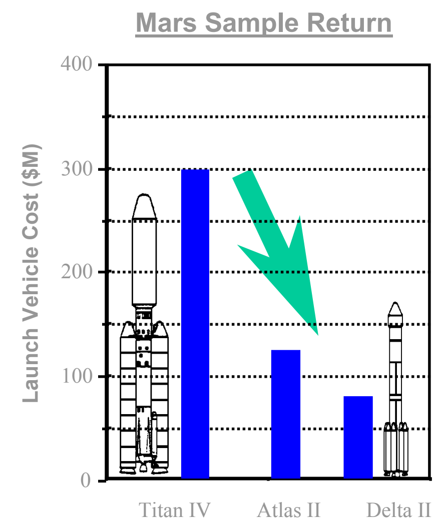
ISRU vs. Non-ISRU Mars Mission Study Results

Mars Sample Return with & without ISRU (Multiple Studies)

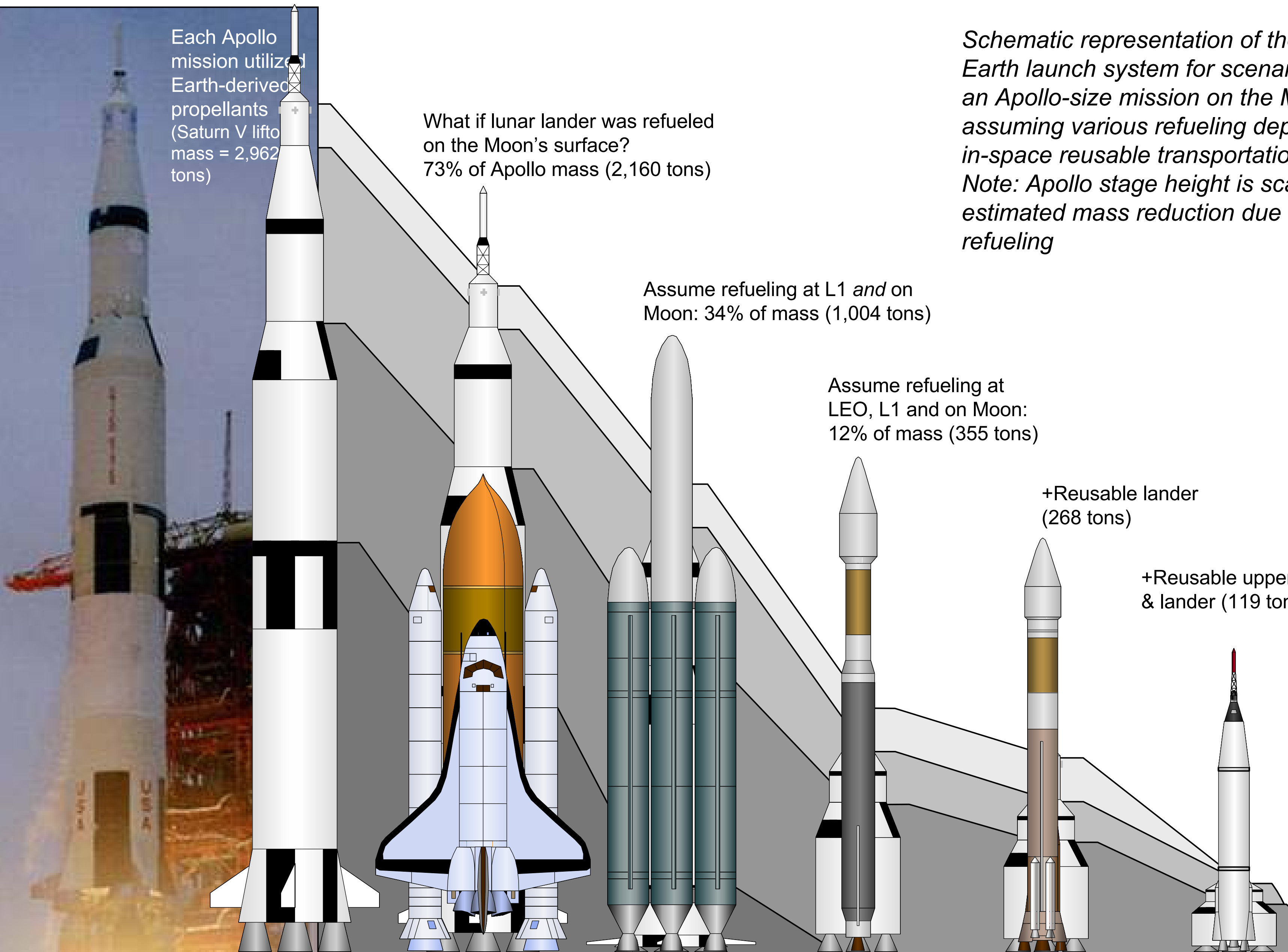
- **20% to 35% reduction** in launch **mass** for Mars Sample Return
- Possible use of Delta II or Atlas II versus Titan IV or Proton **reduces launch cost** by a **factor of 2 to 3**
- ISRU ***enables*** Direct Earth return sample return mission with large sample (5+ kg)
- Propellant production unit for Mars sample return mission is:
  – Same scale of production unit to supply EVA oxygen or EVA fuel cell powered rover
  – Scalable to human mission propellant production package



Human Mars Missions

- **21 to 25% mass reduction** for Human Mars Design Reference Mission
  – Smaller lander = smaller Mars trans stage and Mars orbit capture vehicles
  – Greater mass savings with increasing Delta-V (i.e. higher Mars rendezvous orbit)
- **3.5:1 mass savings leverage** from Mars surface back to Earth, i.e. 30 MT of in-situ propellant production equals >100 MT in Low Earth Orbit

CSM Study: Propellant from the Moon will revolutionize our current space transportation approach



Schematic representation of the scale of an Earth launch system for scenarios to land an Apollo-size mission on the Moon, assuming various refueling depots and an in-space reusable transportation system. Note: Apollo stage height is scaled by estimated mass reduction due to ISRU refueling

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ISRU Enables Highly Capable, Affordable & Sustainable Surface Exploration Infrastructure

Robotic Precursors & Tele-robotic Science


EVA Astronaut w/ Robotic Assistant

EVA w/ Pressurized or Un-Pressurized Rovers


Crewed & Science Landers & Hoppers


☑ ***Power-rich environment enables new science, capabilities, and relaxed power constraints***

- Single main power source produces oxygen & fuel cell reactants for all surface assets (EVA suits, rovers, etc.)
- High power on demand capability
- Swap new fuel cell reactants w/ used water on return with samples

☑ ***Modular common hardware for reduced logistics, higher reliability, and increased flexibility & safety***

- Reduced logistics needs
- Simplified spare parts manufacturing or scavenging possible

☑ ***Production of common mission consumables increases mission effectiveness, sustainability, & provides functional redundancy to minimize risk***

- Resupply EVA O_2 & FC reactants from Rover to extend EVA or in case of emergency

☑ ***Infrastructure is reusable and easily expandable from simple robotic lander to full human presence***

- More assets can be added with increase in production capability
- Increased surface access possible with ISRU
- ISRU hoppers enable surface access at fraction of cost of dedicated lander mission
- MAV size reduced if lander stage is reused with in-situ propellant

ISRU Commonality-Dependency With Other Capabilities

Capability Products To ISRU	Capability	ISRU Products To Other Capabilities
• Solar & nuclear power to support power-intensive ISRU activities	High-Energy Power & Propulsion	• H_2 & ^3He for NTR & fusion; Ar for electric • Solar array and collector manufacturing & assembly • Rectenna fabrication for orbital power beaming • Thermal storage material production & fabrication • Radiation shields for nuclear reactors
• ISRU-compatible propulsion • Delivery of ISRU capabilities to sites of exploration • Electromagnetic launch systems for delivery of ISRU products	In-Space Transportation	• Propellant production and pressurant/purge gases for lander reuse and in-space depots • Aeroshells from Regolith
	Advanced Telescopes & Observatories	• Shaping crater for collector • In-situ construction and fabrication
• Resource location & characterization information • Surface mobility system design & experience	Robotic Access to Planetary Surfaces	• Production of fuel cell reagents for rovers (vs solar arrays or RTGs for certain missions) • Propellant production for surface hoppers or large sample return missions
• ISRU-compatible propulsion • Delivery of ISRU capabilities to sites of exploration	Human Planetary Landing Systems	• Landing pads/plume debris shielding • Propellant production/storage/transfer for lander reuse
• Carbon-based waste products as resource for ISRU	Human Health and Support Systems	• Habitat/shelter fabrication • Gases for inflation & buffer gases • Life support consumable production for backup • Radiation shields from in-situ material • Soil & bio-feedstock for plant growth • Materials for in-situ manufacturing
• Crew/robotics/rovers to perform ISRU surface activities	Human Exploration Systems & Mobility	• Gases for science equipment • Propellants & fuel cell reactants for surface vehicles and aero-bots • O_2 production for EVA
• Robots/rovers to perform ISRU surface activities • Software & FDIR logic for autonomous operation	Autonomous Systems & Robotics	
• Resource location & characterization information	Scientific Instruments & Sensors	

In-Situ Resource Utilization (ISRU)
Capability Breakdown Structure

In-Situ Resource Utilization 1.0

Chair: Jerry Sanders/JSC
Co-Chair: Mike Duke (CSM)

- 1.1 Resource Extraction
  - 1.1.1 Resource Assessment
  - 1.1.2 Resource Acquisition
  - 1.1.3 Resource Separation/ Concentration
- 1.2 Resource & Waste Transportation
  - 1.2.1 Fixed Mechanical Transportation
  - 1.2.2 Mobile Mechanical Transportation
- 1.3 Resource Processing
  - 1.3.1 Mission Consumable Production
  - 1.3.2 Feedstock Production for In-Situ Manufacturing
  - 1.3.3 Feedstock Production for Surface Construction
  - 1.3.3 Feedstock Production for In-Situ Bio Support Systems
- 1.4 Surface Manufacturing with In-Situ Resources
  - 1.4.1 Metallic Part Manufacturing
  - 1.4.2 Polymer/Plastic Part Manufacturing
  - 1.4.3 Ceramic Part Manufacturing
  - 1.4.4 Locally Manufactured Energy Systems
  - 1.4.5 Locally Integrated Systems & Components
  - 1.4.6 Manufacturing Support Systems
- 1.5 Surface Construction
  - 1.5.1 Surface Preparation
  - 1.5.2 Excavation & Tunneling
  - 1.5.3 Structure/Habitat Fabrication
  - 1.5.4 Radiation & Plume Debris Shielding
  - 1.5.5 Landing & Launch Site
- 1.6 Surface ISRU Product & Consumable Storage and Distribution
  - 1.6.1 Surface Cryogenic Fluid & Propellant Storage & Distribution
  - 1.6.2 Processing Reagent Storage & Distribution
  - 1.6.3 Gas Storage & Distribution
  - 1.6.4 Utility Connections & Interfaces
  - 1.6.5 Water storage & Distribution
  - 1.6.6 Hazard Detection & Suppression

ISRU Development & Integration Philosophy

- **Not Everything Can Be Funded Immediately**
- Need *Early, Achievable, & Visible* milestones & successes
- Need to take Evolutionary approach In development & missions
  - Early hardware needs to be achievable, not optimized
  - Early hardware needs to be scalable to future missions
  - Each design/demonstration activity needs to build on lessons learned from previous work and show clear benefit metrics
  - ➢ Research activities and technology development must be continuously performed and focused to enable sustained momentum and growth
  - Capabilities need to be able to grow with growth in:
    - Resource & process understanding
    - Human surface activities
- Mission incorporation potential
  - Robotic precursor to human mission
  - ISRU demo on early human flights
  - Lander/mission dedicated to ISRU process
- No single processes or technology is best
  - Develop two or more approaches if possible to ensure success

Criteria To Evaluate ISRU Activity Priority

- Mission Mass Reduction (immediate & long-term)
  - Ability to provide immediate/early impact on mission
  - Minimum infrastructure/launches required to provide product/service
- Complexity/Risk
  - ISRU Process/Service
  - Compared to “bring from Earth” approach
- DDT&E & mission cost reduction
  - Ability of hardware/technology to be used in multiple applications & destinations
  - Rate of return on investment by Gov or Commercial Enterprise
- Mission risk reduction
- Ability to Enable Mission Goals/Objectives
  - Sustained human presence & long-term self-sufficiency
- ISRU Processing Attributes
  - Reliability/Mean Time Between Repairs
  - Mass of Product/Service vs Mass of ISRU “system”
  - Power Requirement Per Mass of Product/Service
  - Production rate
  - Growth potential
  - % of Earth Consumable (immediate & long-term)
- Enables space commercialization and other applications
  - NASA-Science
  - Military Missions
  - Debris Management
  - Satellite Servicing & Refueling
  - Space Solar Power

Backup

Resource Extraction

- Resource Extraction 13.1
  - Resource Assessment 13.1.1
    - Physical Characterization 13.1.1.1
    - Chemical/ Mineralogical Characterization 13.1.1.2
    - Resource Area Mapping 13.1.1.3
  - Resource Acquisition 13.1.2
    - Atmosphere Collection 13.1.2.1
    - Surface Material Excavation 13.1.2.2
    - Sub-Surface Material Extraction 13.1.2.3
    - Habitat Resources & Waste Collection 13.1.2.4
  - Resource Separation/ Concentration 13.1.3
    - Physical Separation 13.1.3.1
    - Chemical Separation 13.1.3.2
    - Thermal Separation 13.1.3.3
    - Electro-Magnetic Separation 13.1.3.3

Resource & Waste Transport

- Resource & Waste Transportation 13.2
  - Fixed Mechanical Transportation 13.2.1
    - Bucket Lines 13.2.1.1
    - Conveyors 13.2.1.2
    - Pipelines (gas, liquid, slurry) 13.2.1.3
    - Lobber 13.2.1.4
  - Mobile Mechanical Transportation 13.2.2
    - Haulers 13.2.2.1
    - Loaders 13.2.2.2

Resource Processing

- Resource Processing 13.3
  - Mission Consumable Production 13.3.1
    - Oxygen Production 13.3.1.1
    - Propellant & Fuel Cell Reagent Production 13.3.1.2
    - Water Production 13.3.1.3 *Linked to 13.1.2.2, 13.1.2.3, 13.1.3.3 & 13.3.1.2*
    - Buffer & Science Gas Production 13.3.1.4 *Linked to 13.1.2.1, 13.1.3.2, & 13.1.3.3*
  - Feedstock Production for In-Situ Manufacturing 13.3.2
    - Metal Feedstock Production (iron, aluminum, etc.) 13.3.2.1
    - Glass/Ceramic Feedstock Production (Silicon) 13.3.2.2
    - Polymer/Plastic Feedstock Production 31.3.2.3
  - Feedstock Production for Surface Construction 13.3.3
    - Concrete/Bricks 13.3.3.1
    - Fiberglass 13.3.3.2
  - Feedstock Production for In-Situ Bio Support Systems 13.3.4
    - Plant Fertilizer & Soil Prep 13.3.4.1
    - Synthetic Foods 13.3.4.2

Surface In-Situ Manufacturing

- Surface In-Situ Manufacturing 13.4
  - Metallic Part Manufacturing 13.4.1
    - Casting 13.4.1.1
    - Sintering 13.4.1.2
    - Machining 13.4.1.3
    - Extrusion 13.4.1.4
    - CVD 13.4.1.5
  - Polymer/Plastic Part Manufacturing 13.4.2
    - Free-form Fabrication 13.4.2.1
  - Ceramic Part Manufacturing 13.4.3
    - Tape Casting 13.4.3.1
    - Power Casting/Sintering 13.4.3.2
  - Locally Integrated Energy Systems 13.4.4
    - Photovoltaic Cell/Array Production 13.4.4.1
    - Solar Collector/Concentrator Production 13.4.4.2
    - Rectenna/Power beaming Construction 13.4.4.3
    - Thermal Storage Media & System Construction 13.4.4.4
    - Battery Material/Assembly Construction 13.4.4.5
  - Locally Integrated Systems & Components 13.4.5
    - Motors & Actuators 13.4.5.1
    - Surface Transporters/Vehicles 13.4.5.2
    - Frame/Tower Fabrication & Assembly 13.4.5.3
    - Aeroshell Fabrication & Assembly 13.4.5.4
  - Manufacturing Support Systems 13.4.6
    - NDE 13.4.6.1
    - Metrology 13.4.6.2

Surface Construction

- Surface Construction 13.5
  - Surface Preparation 13.5.1
    - Virtual-Reality Site Development 13.5.1.1
    - Surveying 13.5.1.2
    - Road & Pathway Construction 13.5.1.3
    - Grading 13.5.1.4
    - Surface Stabiliation 13.5.1.5
    - Molding Craters for Telescopes 13.5.1.6
  - Excavation & Tunneling 13.5.2
    - Tunneling 13.5.2.1
    - Drilling 13.5.2.2
    - Trenching 13.5.2.3
  - Structure/Habitat Fabrication 13.5.3
    - Concrete/Ceramic Brick 13.5.3.1
    - Sintering/Casting Ceramic & Composite Structures 13.5.3.2
    - Metal Pressure Vessels 13.5.3.3
    - Pressurized Environment Sealing 13.5.3.4
    - Inflatable Structures from In-Situ Manufactured Products 13.5.3.5
    - Structural Glass & Windows 13.5.3.6
    - Bonding/Welding 13.5.3.7
  - Radiation Shielding/ Plume Debris Shielding 13.5.4
  - Launch & Landing Site 13.5.5
    - Surface Leveling 13.5.5.1
    - Debris Removal 13.5.5.2
    - Flame Trenching/Plume Directing 13.5.5.3
    - Concrete Surfacing and Surface Sintering 13.5.5.4
    - Fluid Distribution and Fixed Line Emplacement 13.5.5.5
    - Electro-Magnetic Launcher Assembly 13.5.5.6

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Surface Consumable & Product Storage and Distribution

- Surface ISRU Product & Consumable Storage Distribution 13.6
  - Cryogenic Fluid Storage & Distribution 13.6.1
  - Processing Reagent Storage & Distribution 13.6.2
  - Propellant Fluid Storage & Distribution 13.6.3
  - Gas Storage & Distribution 13.6.4
  - Utility Connections & Interfaces 13.6.5
  - Water Storage & Distribution 13.6.6
  - Hazard Detection & Suppression 13.6.7

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ISRU Capability Team

Chair: Gerald (Jerry) Sanders (JSC)
Co-Chair: Mike Duke (Colorado School of Mines)

NASA (8)

Kris Romig (JSC) - Chair Secretary
William Larson (KSC)
Lou Salerno (ARC)
Don Rapp (JPL)
Kurt Sacksteader (GRC)
Peter Curreri (MSFC)
David McKay (JSC)
Stu Nozette (HQ)

Academia (2)

Brad Blair (Colorado School of Mines)
Leslie Gertsch (Univ of Missouri/Rolla)

Industry (3)

Eric Rice (Orbitec)
Larry Clark (Lockheed Martin)
Robert Zubrin (Pioneer Ast.)

ISRU Challenges & Technology Drivers

- **In-Situ Resource Excavation & Separation:** Efficient excavation of resources in extremely cold (ex. Lunar permanent shadows), dusty/abrasive, and/or micro-g environments (Asteroids, comets, Mars moons, etc.)
  - Efficient, wear tolerant (dust insensitive) small grain regolith excavation and collection
  - Efficient "hard" resource excavation and collection
  - Efficient thermal (solar, electrical, or microwave) furnace for volatile extraction from resources
  - Flexible and efficient techniques for mining, tunneling, drilling, and other material manipulation in unknown materials and harsh environments

- **In-Situ Resource Processing & Refining:** Affordable, reliable and effective local production, using local materials of key mission/systems resources (including life support system consumables, propellants, etc.). Processing and manufacturing techniques capable of producing 100 times their own mass of product in their useful lifetimes.
  - Microchannel and etched chemical/thermal processors for significant mass, volume, & power reduction
  - Efficient system-wide thermal management to minimize power requirements
  - Chemically efficient processing to minimize or eliminate need for Earth consumables

- **Manufacturing With In-Situ Resources an/or In-Situ Products:** Affordable and flexible local manufacture of robust, high-value components, systems elements, and systems (e.g., structural elements, tankage, solar arrays, spare parts for systems, etc.) in lunar and planetary venues using 'imported' and local materials. In-situ manufacture of parts and equipment with the minimum of required equipment and crew training

ISRU Challenges & Technology Drivers (Cont.)

- **Surface Construction:** Affordable and flexible construction of robust local structures (e.g., radiation shielding, site preparation, habitats, transportation infrastructures, etc.) in lunar and planetary venues using local (or 'imported') materials. Construction and erection techniques capable of producing complex structures from a variety of available materials.
  - Conversion of Earth construction techniques to space environment
    - Little or no atmosphere (spraying and curing difficulties)
    - Extreme temperature variations
    - Variable g-levels
    - Suited astronauts

- **Surface ISRU Consumables/Product Storage and Distribution:** Affordable, reliable and effective local management, handling, transport and storage of key consumables and products.
  - Power efficient and long-life refrigerators and cryocoolers for separation, liquefaction, and storage
  - Mass, power, and efficient insulation and storage tanks
  - Fluid transfer systems and couplings with dust mitigation
  - Efficient and capable surface transportation systems

Capability Roadmap Products

- Overall description of the capabilities or knowledge needed
  - Primary purpose to fulfill Vision
  - However, need to understand potential of revolutionary technology to further the NASA capability
- Benefit of the capability, **why is it needed, (e.g. reduce cost, reduce mass, mission enabling, reduce risk,etc.)**
- Background and relevant history of related developments**, including mission application**
- Driving requirements and delivery dates
  - Agency Strategies (which of the 13 strategies), that drive the need for the capability (make assumptions until Strategic roadmap teams mature their product, then make adjustments)
  - Reference Mission Architecture Assumptions including operational scenarios (To be provided on or before October 19)
  - If Reference Missions are used other than those provided in this framework then add:
    - Description of the reference mission
    - Operational scenario of the reference mission
    - How it aligns with spirals, if applicable
    - Rationale for why it needs to be added
  - External requirements, including national priorities
  - Program or project requirements
  - Key variables driving technology choices (e.g. flight frequency, crew size, mission duration).

Capability Roadmap Products (cont)

- Identification of key component technologies and a description of how they are integrated to provide the capability
  - What is needed to turn technologies into capabilities
  - Identification of key national expertise/assets/facilities, that are needed for the capability
  - Summary of potential revolutionary or advanced concepts for achieving the capability
- Assessment of the current state of the art of key component technologies
  - Leading technology candidates
  - Current technology readiness levels
  - Key gaps between state of the art and required performance levels
  - Description of development to close the identified gaps
  - Estimated date to reach a TRL of 6 for key technologies
  - Identification of metrics to evaluate development progress and ultimately judge whether the capability has been achieved (Figures of merit for the technology)
- Assessment of the current state of the art of the overall capability and key component technologies
  - Current capability readiness level
  - Description of capability development required, level of performance and expected deliverables
  - Estimated date to reach readiness of the capability necessary for a mission and under what assumptions
  - Identification of major challenges in meeting the required capabilities, assessment of risk, alternatives or offramps; consequence of not achieving the capability

Capability Roadmap Products (cont)

- Estimated Funding required for Capability development or knowledge development **(Estimate funding within half an order of magnitude at the capability level and technology level); (Runout cost from the current state of the art until delivery of the product)**
- High level roadmap identifying capability development for 2005- 2030
- Backup roadmaps that show the sub-capability development and component technologies **for 2005-2030 (format to be provided)**
- Dependency on other Roadmaps
  - Relationships to strategic roadmaps
  - Relationships to other capability roadmaps
- Delivery of final report with the above content
- Appendix**: Supporting Documents, references, (e.g. CRAI data)**